Space-Hardware Design For Long Life With High Reliability

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Kcy Words: Design, test, hardware, space, long life., reliability, NASA

SUMMARY & CONCLUSIONS

In 1991, the Cassini Project, NASA's planetary project to place a spacecraft in orbit about Saturn, funded a study at the. Jet Propulsion Laboratory (JPL) to identify rules for design and test of hardware required to function reliably in space for very long lifetimes. T 'Wxlly-nine subjects were considered comprising 130 specific rules related 10 long-life issues such as accelerated life. testing, cycling of mechanical devices, selection and application of par 1s, semiconductor junction temperatures, and woisl-case analysis for long life. The study was subsequently published as a J}'], document. One major conclusion of the. workshop was that unattended space missions extending out to 25 years or more arc feasible.

1. INTRODUCTION

In 1991, the Cassini Project, NASA's planetary project to place a spacecraft in orbit about Saturn, funded a study at the Jet Propulsion 1 aboratory (J}'],) to identify rules for design and test of hardware required to function reliably in space for very long lifetimes. The team formed for this study was composed of JPL engineers and consultants who were familiar with the Voyager (Jupiter, Saturn, Uranus, and Neptune) spacecraft design and test philosophy, as well as other space hardware which employed high reliability practices that led to extended life,

The Voyager spacecraft was deemed an appropriate baseline for the study team from which to start, because (1) it represents a J}'], program which addressed long life in the. design and test approach, ('2) it was not over-constrained in resource limitations in becoming a long-life. with high-reliability mission, (3) it is a highly complex spacecraft that has functioned remarkably well, and (4) it has demonstrated k)l]g-life performance for over 15 years, with both spacecraft operating continuously.

The team met over an eight-month period, culminating in a one-day workshop. The study was subsequently published as a JPL document (Ref. 1). This paper reports on the study and the one-day workshop.

11, STUDY PURPOSE AND SCOPE

The purpose of the study was to develop rules for kmg-life. with high-reliability space missions. The criteria for the consideration of a hardware issue as a "lmlg-life with high-reliability" rule. were: (1) Rules 10 mitigate changes in physical properties due to passage of time, use and operation, and environmental exposure; (2) design strategies that reduce or eliminate susceptibility of system function to changes in physical properties due to operations or environmental exposure; (3) analysis strategies that assure the identification of possible changes in physical properties or susceptibility of system functions to changes in physical properties; or (4) processes which provide an estimate of the magnitude or likelihood of the expected change in physical properties.

The wide.sl possible range of hard wa re rule.s were considered consistent with three constraints: (1) Software and mission rule.s were addressed only 10 the extent they affected hardware performance; (?) the rules developed were applicable to a single spat.c.claf[, and multiple spacecraft to achieve mission success were not considered; and (3) high reliability rules were considered only in their relationship to long life.

III. SUBJECTS AND RULES

Twenty-nine subjects were considered comprising 130 specific rule.s related to long-life issues such as accelerated life testing, cycling of mechanical devices, selection and application of parts, semiconductor junction temperatures, and worst-case analysis for long life. The subjects were:

Analysis	Burn-in
Cables	Components
Degradation	Design verification
Electrical	Environment
Fabrication	Faults
Handling	Inheritance
Materials	Mechanical
Mission	New technology
Operations	Packaging
Parts	Power
Product assurance	Propulsion
Redundancy	Slip rings
Software	Structural
Testing	'1'est facilities
Thermal	

in subsequent sections of this paper, some of the 130 design rules are presented, along with the rationale for each of the design rules.

IV. RULE: GRACEFUL DEGRADATION

The design rule is that the spacecraft system should be designed such that failures due to exposure beyond expected life extremes (e.g., excessive temperature excursions, excessive radiation, etc.) will lead to gradual degradation of function rather than catastrophic failure.

The rationale is that due to unanticipated operational problems the mission parameters of temperature and lifetime may exceed the expected limits. Out-of-specification circuit operation can still yield useful information of only degraded accuracy as opposed to step changes which yield very little information. If the degradation is predictable, data can be corrected to minimize errors.

V. RULE: ENVIRONMENTAL TEST MARGINS

The design rule is 10 perform environmental-qualification tests on dedicated qualification hardware at levels and durations well beyond maximum allowable. flight limits. Perform flight-acceptance tests on all flight hardware. at levels exceeding the allowable flight envelopes.

The rationale is that in order to validate effects from all possible conditions of flight-hardware exposure in a timely manner, it is necessary to have an early set of tests which adequately exhaust questions of marginality and which are not compromised by the test article's possible flight status.

VI. RULE: SEMICONDUCTOR JUNCTION TEMPERATURE

The design rule is to maintain semiconductor junction temperatures to less than 60^{o}C during long-duration flight operations. (Short-term inflight excursions associated with transient events arc. exceptions.)

The rationale is that this proved to be feasible on JPL planetary missions by establishing qualification-test temperatures of less than or equal 10 75^{o}C while limiting part-junction temperatures 10 110^{o}C. The lower junction temperatures result in exponentially lower failure rates, e.g., the increase in life by reducing flight-junction temperatures from 85^{o}C to 60^{o}C is as much as one order of magnitude.

VII. DESIGN & TEST TEMPERATURE LEVELS

The design rule is to design assemblies to baseplate temperature limits of -30^{o}C 10 +85^{o}C. If the thermal control allowable flight range cxc.c.eels the range of +5^{o}C to +50^{o}C, then design for allowable flight temperature limits +/-3 5^{o}C. For assemblies with internal heal gene.ralion (such as electronics), perform a thermal analysis in sufficient detail 10 define design temperatures for all components based on the above boundary conditions. Perform thermal environmental qualification testing in vacuum from -20^{o}C 10 +75^{o}C, and acceptance testing in vacuum from 0^{o}C to + 55^{o}C. If the allowable flight range exceeds + 5^{o}C to + 50^{o}C, then qualify to allowable flight temperatures + /-25^{o}C, and acceptance testing to allowable flight temperatures + /-5^{o}C.

The rationale is that the allowable flight temperature range of +5^{o}C to + 50^{o}C provides a broad range to reduce the overall complexity of the system thermal-control design process and to cover wors[-case assumptions and prediction uncertainty. Hydrazine freezes just below +5^{o}C, and a typical electronic bay reaches + 50^{o}C after direct exposure to the sun after one hour at the Earth-sun distance. When combined with the rule of the preceding section (Semiconductor Junction Temperature), this assures satisfactory flight performance at low semiconductor junction temperatures, and demonstrates compliance with constraints on the flight hardware exposure during test.

VIII. RULE: WORST CASE ANALYSIS

The design rule is 10 perform worsl-case analyses on all electronic assemblies at 10^{o}C beyond qualification ten-tures to assure performance margins with respect to possible. mission contingencies.

The rationale is that flight experience (e.g., Magellan and Voyager) have revealed the need for flexibility and trades in temperature and operating modes as parts degrade and fail.

IX. RULE: ELECTRONIC-PART CLASS

The design rule is to usc only Class S or Class S equivalent electronic parts.

The rationale is that low failure rates arc guaranteed by virtue of required vendor lest experience on parts fabricated on production lines with certified controlled processes. High reliability is ensured by required wafer lot acceptance, longer burn-in PIND testing, X-Ray inspection, 100% pull tests and the recording of parameter burn-in drifts.

X. RULE: PARTS BURN-IN

The design rule is that all flight parts should be subjected 10 burn-in. Burn-ins are not 10 be performed at stress levels which potentially introduce new failure mechanisms or for durations which would degrade expected life.

The rationale is that burn-ins should be optimized for the removal of latent dc.feels and early failures. The effectiveness of burn-in at removing early failures can be determined from the manufacturer's historical data comparing failures during turn-in and failures during life. test from detailed time-to-fail data taken during burn-in. Additional bum-in is beneficial so long as the hazard rate at the end of the burn-in exceeds the hazard rate at end of mission.

XI. RULE: ELECTRONIC HARDWARE CLEANING

The design rule is that cleanliness should be specified and maintained according to a contamination control plan during all assembly phases of hardware. Cleaning should be accomplished with qualified procedures and approved solvents. Cleanliness of hidden areas must be inspected prior to continuing with the next assembly phase.

The rationale is that a common source of problems in electronic equipment is contamination such as flux residue. Removing contamination from components is common in electronics, but can be potentially dangerous to equipment when an incorrect solvent or procedure is used. Inadequate procedures can cause such life-related malfunctions as electrical leakage and dielectric breakdown due to bridging by conductive particles and bondline failure of joints mused by poor adhesion to a contaminated sur face,

XII. RULE: ACCELERATED LIFE TESTING

The design rule is that life tests should be performed on units exhibiting life-lil]liting characteristics as part of qualification testing to reveal possible systematic defects. The equipment-test duration should be sized to include both ground test and mission requirements with margin. The test plan should include some test time at expected flight extremes.

The rationale for the life-test rule is in part derived from the Voyager 2 spacecraft experience. The Voyager 2 azimuth drive scan actuator seized at 358 revolutions al Saturn encounter. Subsequent testing of the prototype resulted in failure under similar conditions at 350 revolutions. The mission requirement was for 4,000 revolutions. No life verification testing was done.

XIII. RULE: POWER-ON VIBRATION TESTING

The design rule is that flight electronics should be designed such that the design does not preclude power-on operation during vibration and shock testing.

The rationale is that the mutual exclusion of power-on and vibration or shock testing eliminates one of the most C.f[cc.live investigative processes for detecting intermittent failure that arc likely to reoccur during a long mission.

XIV. RULE: ADHESIVE JOINTS

The design rule, is that design of mission-critical adhesive joints should utilize a mechanical fastener as a backup.

The rationale is that kmg-life. environments of ultraviolet exposure or thermal cycling can cause. failure of adhesive joints. These joints should be designed to accommodate either rivets or threaded fasteners.

XV. RULE: ELECTROMAGNETIC INTERFERENCE

The design rule is 10 design and build the spacecraft as a Faraday cage to isolate all spacecraft electronics from the external electromagnetic environment.

The rationale is 10 provide a basic electrostatically-shielded box containing all electronics, and have all exterior electronics and wire contained in the.ir own I;ara(iay-cage boxes and cable shielding. Treat science instruments, which must have viewing apertures, as exceptions to this rule., but ensure that they arc immune 10 electromagnetic fields from the exterior, and that they do not contribute excessively 10 the external electromagnetic environment.

XVI. RULE: CYCLING OF MECHANICAL DEVICES

The design rule is that mechanical devices that function in a cyclic manner during the mission should demonstrate a life capability with greater than 100% margin.

The rationale is that wearout is a function of lubrication, coefficients of friction, unit pressures, and other factors. A 100% margin should not significantly increase weight.

XVII. RULE: FORCE AND TORQUE MARGINS

The design rule is to design and demonstrate a positive margin for the full range of dc.vice motions at end-of-life conditions, including restart from any position in the full range of motion. Do not rely on momentum to overcome frictional forces. Use the largest possible margins of operation in all devices consistent with other constraints.

The rationale is that forces and torques must overcome opposing forces, torques, and friction. These opposing form, torques, and friction may change with time, temperature, and various environments that arc not always predictable.

XVIII. RULE: THIN-MEMBRANE CORROSION

The design rule is 10 design membranes (e.g., burst-rfisks) to accommodate long-term exposure to the con osive effects of oxidizing propellants.

The rationale is that the thin membranes of burst-disks arc designed to rupture al a set differential pressure across the membrane. The thickness and stress-capability of such membranes arc affected by corrosion on long-cl ural ion missions.

XIX, RULE: ADAPTIVE MISSION STRATEGIES

The design rule is to establish adaptive mission strategies that can accommodate failures as well as unanticipated opportunities.

The rationale is that adaptive mission strategies increase the probability of mission success as well as providing for mission enhancement. For example, an encounter with Titan, the major satellite of Saturn, was a significant objective of the Voyager 1 spacecraft. The Voyager-2 spat.cadl could be retargeted for a Titan flyby if Voyager 1 failed.

XX. WORKSHOP

The workshop was held at JPL on March 5, 1992. Eleven non-JPL representatives gave. their critique of the study report. The workshop was divided into five subgroups for identification and characterization of specific rule.s and proposed actions. The subgroups were: parts, reliability modeling, new technology, risk management concepts, and mechanical processes. Rules discussed included the usc of failure.lhysicsin the selection of parts; the use of functional redundancy; rules for the application of new technology; the implementation of design rules and the incorporation of "lessons learned"; the proper interpretation and design for "random failures"; and the necessity to test systems the way they are to be flown, and then to ffy them the way they were tested. One major conclusion of the workshop was that unattended space missions extending out to ?.5 years or more were feasible.

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of the Cassini Project for chartering and funding the study, and the efforts of the other JPL engineers (Genji Arakaki, Samuel Brunstein, Sarah Gavit, Bruce Hancock, Doug Hess, Charles Jennings, Harry Peacock, and Joe Savino) and the consultants (Robe.rt Brodsky of USC, Frank Carr of NASA Headquarters retired, Halsey Chenoweth of Westinghouse Electric Company, Larry Crow of AT&T Bell Laboratories, Ken Curry of JPL retired, Irv Doshay of TRW retired, Herbert Hecht of SOHAR, Charles Hutchins of Texas Instruments retired, Duncan MacPherson of Hughes Aircraft retired, Dan Mulville of NASA Headquarters, Bill Read of JPL, retired, and Kam Wong of Kambea Industries retired) who participated in the study or the one-day workshop. This research was carried out at the Jet Propulsion laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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1. T. E. Gindorf and G. B. Murphy, *Long Life/High Reliability Design and Test Rules study Report*, JPL Internal Document D 9899, Jet Propulsion Laboratory, Pasadena, California, July 1992.

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Tom E. Gindorf received a B.S. in physics from Texas Technology University and a M.S. in systems management from the University of Southern California. In 1962, he joined JPL and worked in the solar-thermal-vacuum testing of JPL spacecraft systems. In 1966, he was the supervisor of the Thermal Vacuum Environmental Requirements Group. Later he was the Voyager Environmental Requirements Engineer, and was responsible for the environmental design compatibility and test requirements of the Voyager spacecraft. For the.l)asldc.cadc he has served as the Manager for the Reliability Engineering Section. He received the NASA Exceptional Service Medal for his work as chairman of the Voyager Radiation Coordination Committee. He is an advisor to the Aerospace Testing Seminar Executive Committee, and a past member of the Southern California Test Laboratory Manager's Group and the IES.

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